Optimization Using Sensitivity Analysis

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Nomenclature

N_{X_B} = line load on motor skirt in baseline configuration, lb/in.
N_{X_N} = line load on motor skirt with modified stiffness in zone N, lb/in.
SF_N = sensitivity factor for zone N, lb/in./lb
t = thickness, in.
ΔWT_N = weight change associated with stiffness change in zone N, lb

Abstract

THIS paper describes a general sensitivity analysis and design optimization approach. The approach is presented by example as used in optimizing the structural shell used for the airborne support equipment which supports the inertial upper stage in the Space Shuttle (orbiter) payload bay. The paper illustrates that major improvements in design can be made with a simplified sensitivity analysis.

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The inertial upper stage (IUS) is a propulsion vehicle used in the Space Shuttle to transport payloads further into space once the orbiter establishes low Earth orbit. The airborne support equipment (ASE) supports the IUS in the orbiter payload bay. The sensitivity study presented here was used to optimize the aft ASE structural shell with specific criteria being to reduce the peak line load on the solid rocket motor case to an ultimate load of 3000 lb/in.

A baseline aft ASE cylindrical shell design was tailored using conventional design/analysis techniques to provide adequate strength and produce an acceptable peak line load on the solid rocket motor case. Skin gages were increased at the top and bottom of the shell to draw the load away from the critically loaded sides. The sculptured skin thicknesses are shown in Fig. 1. This initial sculpturing was accomplished without the benefit of a sensitivity analysis/optimization.

A sensitivity analysis was initiated to determine which skin gages had the greatest effect on the peak line load and which construction type was most efficient. At this stage of the development isogrid, waffle, and longitudinally stiffened skin panel construction were being considered.

An internal loads analysis for the baseline structure (shown in Fig. 1) consisting of the aft ASE and a portion of the IUS vehicle was accomplished using a finite element model computer solution. The cylindrical shell was then divided into a number of structural zones. Additional internal loads computer solutions were completed in which the sensitivities of the motor case line load to axial, circumferential, and shear stiffening were determined. The axial stiffness sensitivity values are shown in Fig. 2. The definition and interpretation for the sensitivity factor are

$$SF_N = \frac{N_{X_B} - N_{X_N}}{\Delta WT_N}, \frac{\text{lb/in.}}{\text{lb}}$$

$SF_N > 0$ Increase in motor skirt line load with an associated weight increase

$SF_N < 0$ Decrease in motor skirt line load with an associated weight increase

Note: Equation is valid for compressive (negative) N_{X_B} and N_{X_N}.

Three major trends were observed regarding the aft ASE sensitivity analysis:

1) There are large variations in the sensitivity to axial stiffness varying from strongly positive in the immediate areas of the peak load locations to strongly negative values in the adjacent areas.

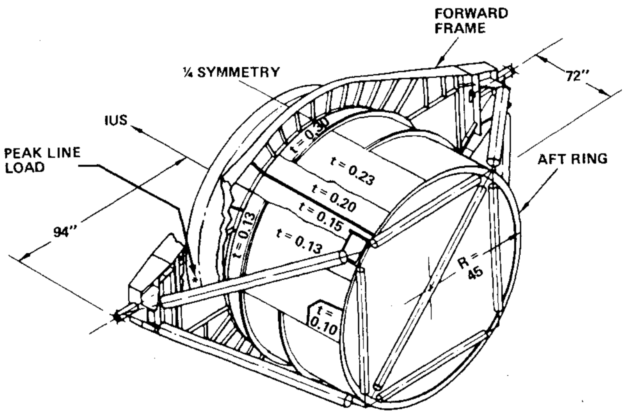

Fig. 1 Baseline aft ASE configuration sculptured cylindrical shell.

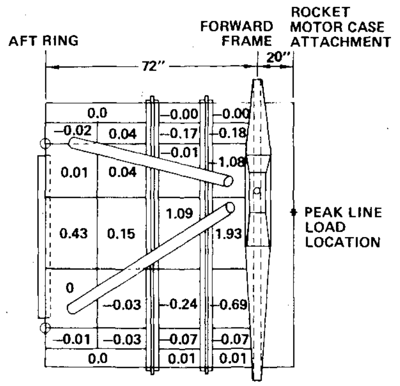

Fig. 2 Sensitivities of maximum line load to local axial stiffnesses.

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2) The peak line load was not sensitive to circumferential stiffening.

3) The analysis displayed a general positive (adverse) sensitivity throughout the entire shell to shear stiffness.

From the sensitivity study it was concluded that isogrid construction was not a good selection due to its high shear stiffness. Waffle construction was also removed from consideration due to the lack of sensitivity to circumferential stiffening. The cylinder was then redesigned using a minimum weight longitudinally stiffened machined panel construction with particular attention given to minimizing the skin gages to reduce the shear stiffness of the cylinder.

The sensitivity analysis and optimization is comprised of five basic steps:

1) Determine the parameters to be minimized or maximized. (In the example these values are the peak line load on the solid rocket motor case and weight of the ASE shell.)

2) Determine the baseline or starting values.

3) Determine the sensitivity factors for values to be minimized or maximized for each change to the baseline. (In the example the shell axial, circumferential, and shear stiffness were reduced to half their baseline value one at a time for each shell zone and the change in motor case line load determined.)

4) Use the sensitivity values to make appropriate modifications to the baseline.

5) Determine a new baseline from the previous iteration and do a new sensitivity analysis if required.

Obviously optimization using sensitivity analysis is a highly nonlinear problem which might appear to necessitate numerous expansive iterative analyses. However, it is important to recognize that the sensitivity varies a great deal throughout the system. Thus, from a designer's view, major improvements in the system can be made knowing the simple sensitivity parameters described herein.